Challenges and Opportunities in Heavy Duty Combustion Development

Carl Hergart

Combustion Research, Caterpillar Inc.

Outline

- Background:
  - Engine system has to satisfy a range of **requirements**:
    - Customer needs: initial cost, fuel consumption, transient response, reliability & durability, and noise
    - Engine robustness to fuel feedstock (bio, synthetic etc.), thermophysical properties (e.g. volatility, viscosity), cleanliness (e.g. water, particles), and sulfur levels
    - Regulatory: Tier 4, GHG, particle size, OBD
- Technology areas:
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  - Air system (turbochargers, EGR-system)
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  - Aftertreatment (DPF, regeneration system, NOx aftertreatment etc.)
- Experimental facilities:
  - Single-cylinder engine
  - Spray lab
- Simulation tools:
  - Cycle simulation
  - CFD
- Some current gaps

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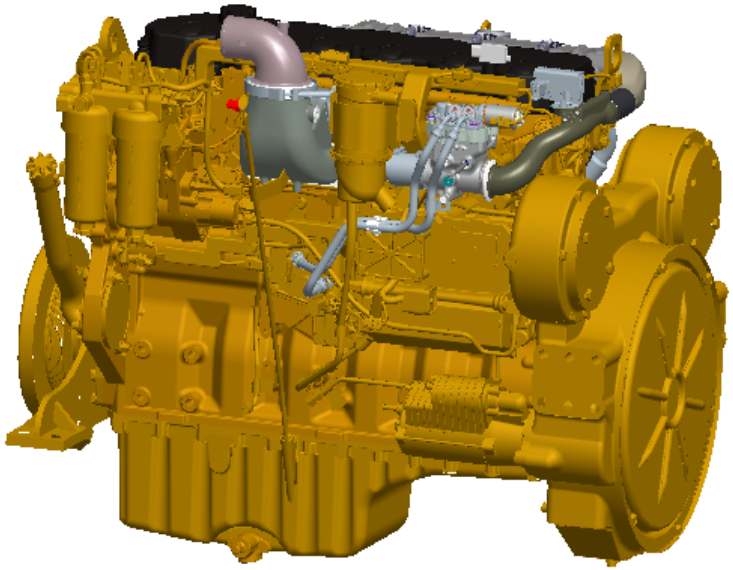
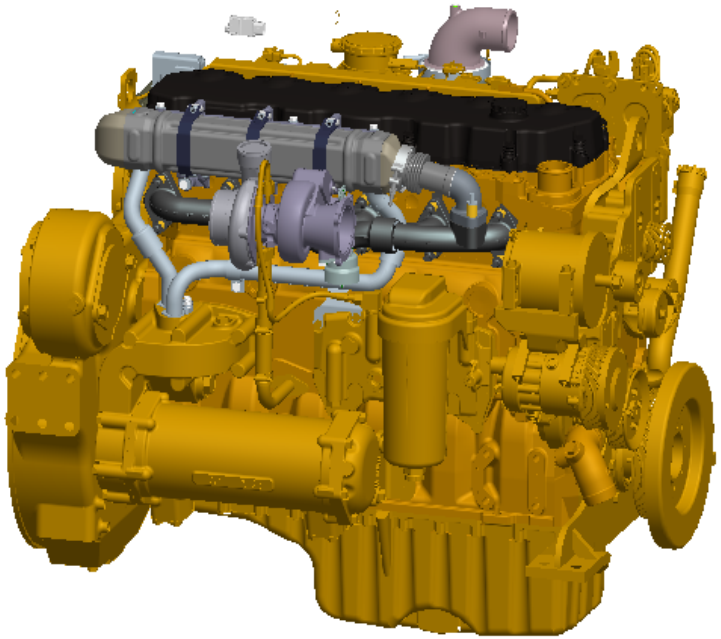
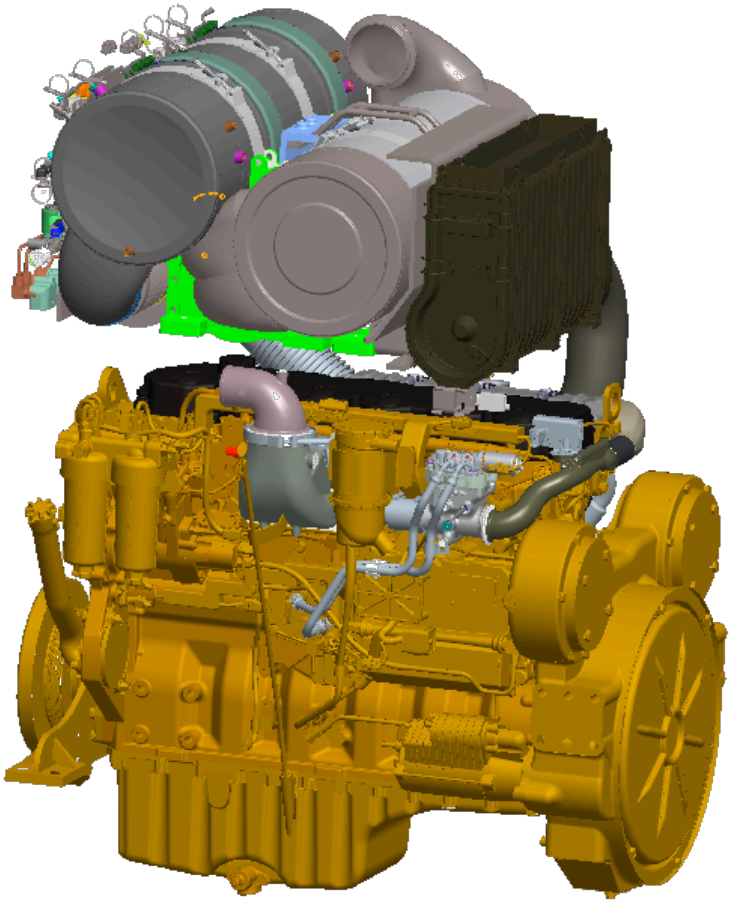
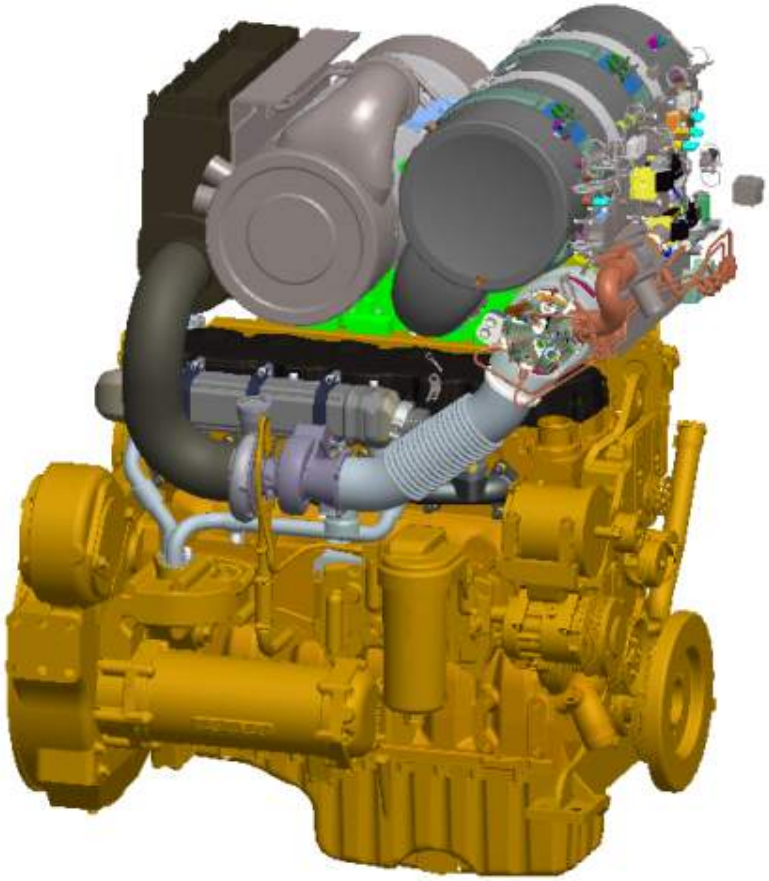
C9 ACERT Engine with NOx Reduction





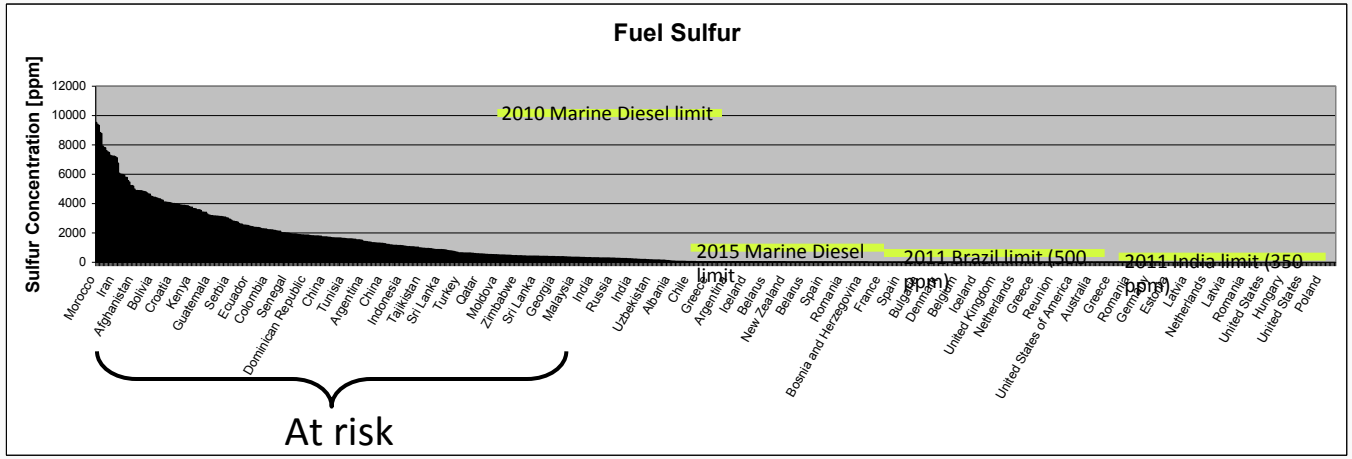
C9 ACERT Engine with Clean Emissions Module



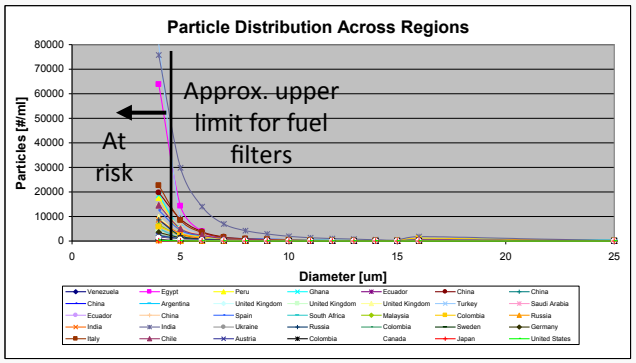


World Fuels Study

- **Context:** The world fuels study tested fuel samples from over 100 countries.
- **Findings:**
  - The fuel sulfur level, which may affect aftertreatment performance varied significantly across different regions of the world

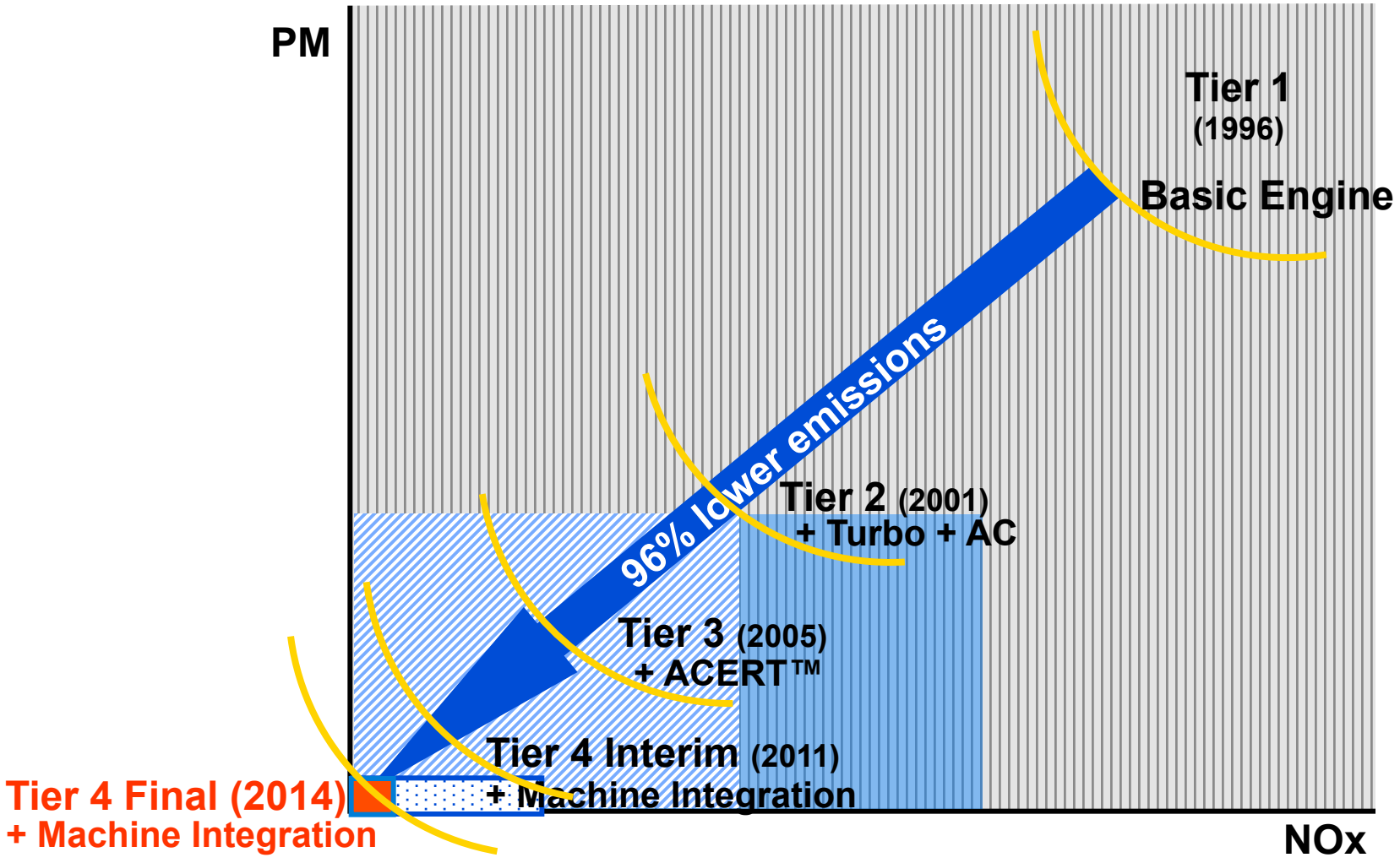


  - The fuel particulate content, which affects fuel system performance (filtration) also varied greatly and exceeded acceptable limits in ~15 countries



Countries with high-sulfur fuel today will represent half of the market in 2020 assuming no changes are made

US EPA Off-Highway Regulations



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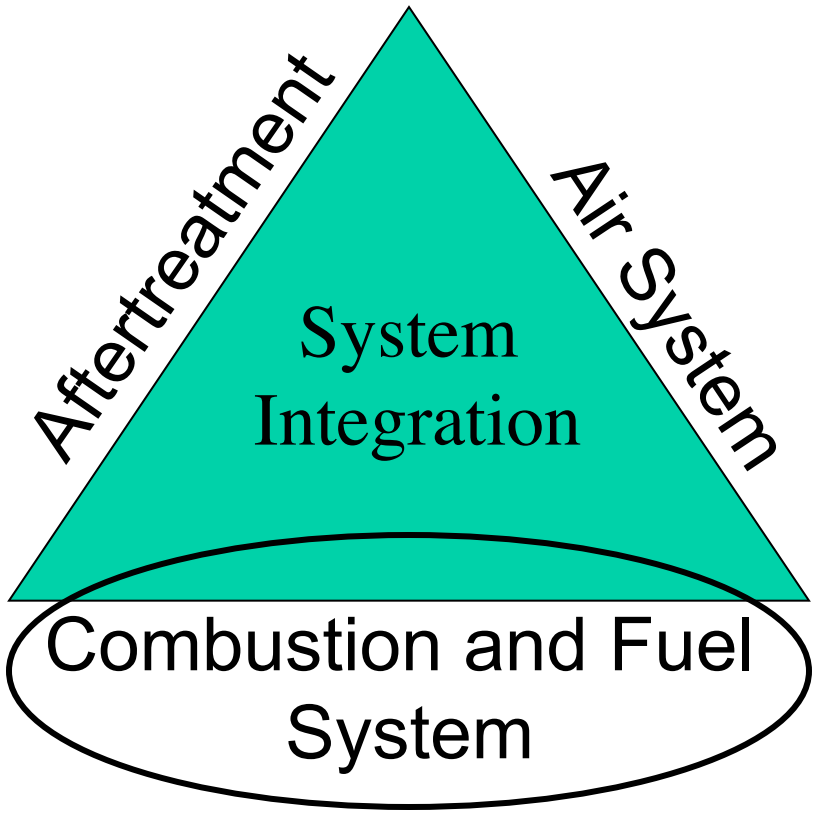
Combustion Technology Building Blocks

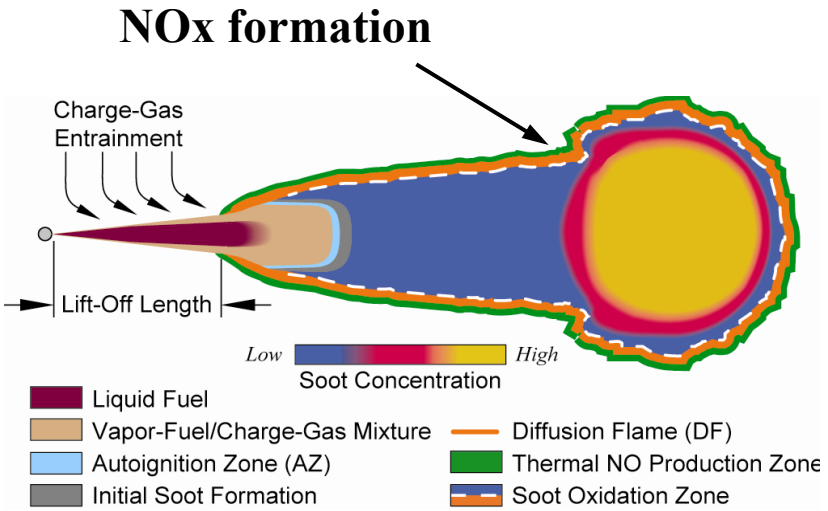
- Injection Pressure
- Injection Rate Shape
- Injector Nozzle Configuration
- Piston Bowl Design
- Valve strategies
- Increased PCP
- Advanced turbocharging
- Reduced Friction
- Reduced Heat Rejection
- Fuel Formula
- Transient optimization

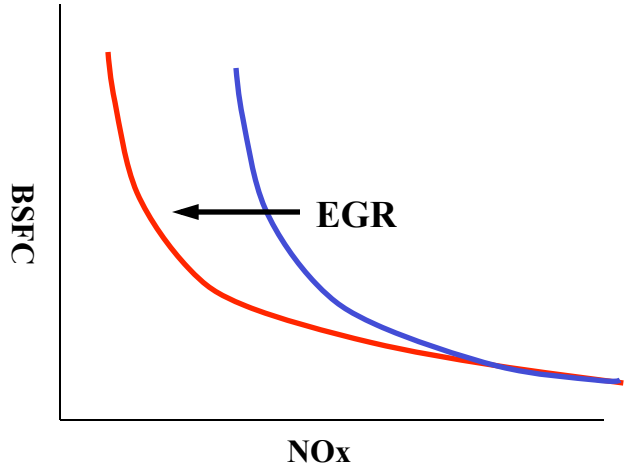


NOx emissions

- NOx formation @ T > 2800K
  - diffusion flame region surrounding the combusting spray

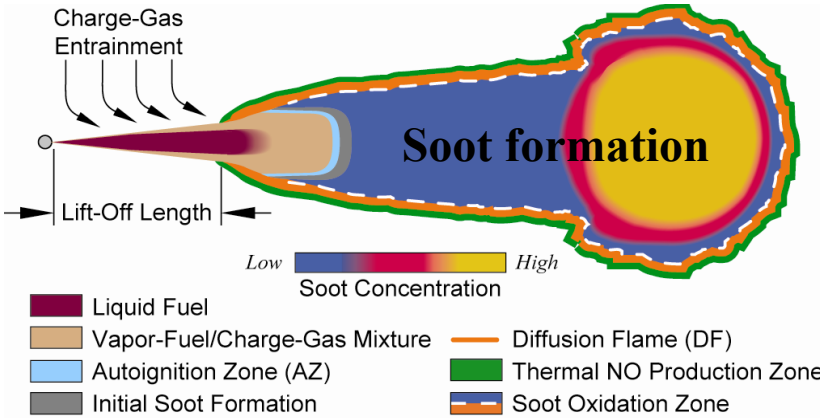
- Control NOx by reducing flame temperature
  - retarding combustion phasing → increases BSFC
  - dilution via EGR
    - increase mass per mole O2 (for diffusion combustion)
    - also increases c_p of gas (CO2, H2O)
    - increases heat capacity of gas per O2
      - → lower flame temp
  - lower O2 has implications on soot emissions





Soot emissions

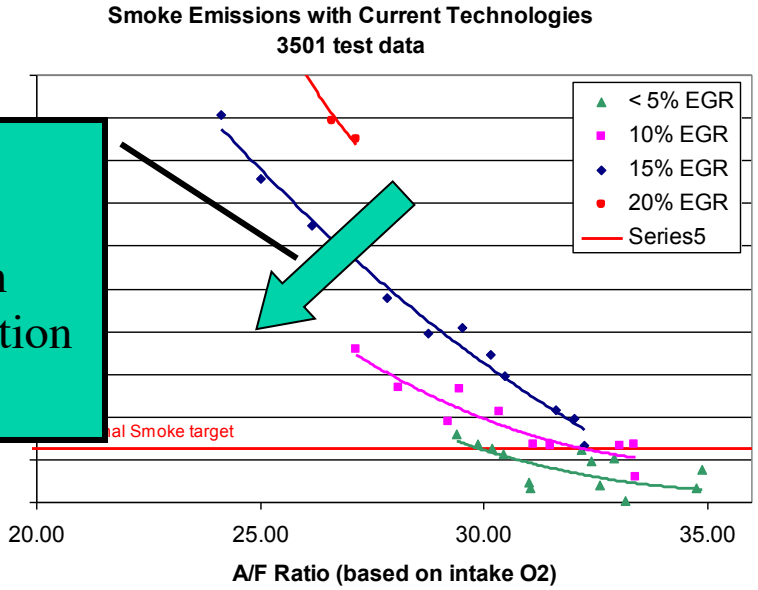
- Soot formation
  - –fuel-rich core of spray (> 2)
  - –gas (O2) entrainment important



Dec, J.: SAE Technical Paper 970873

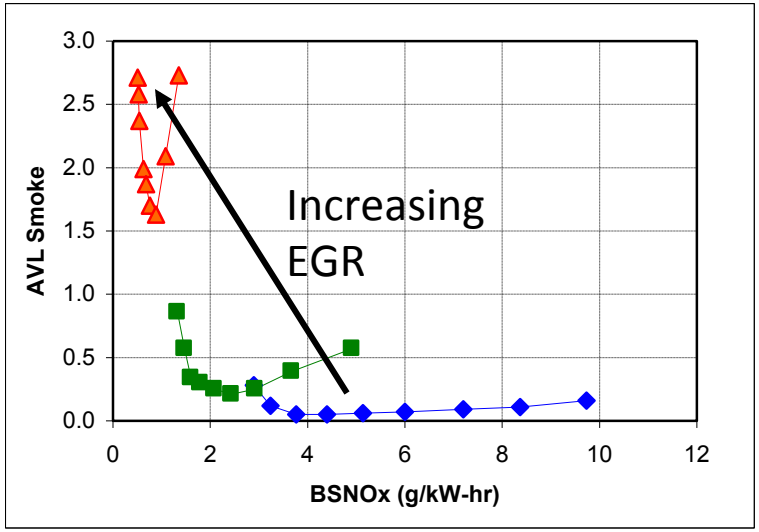
- Soot oxidation
  - –mixing, time and temperature
  - –air (O2) utilization
    - •spray penetration
    - •bulk gas motion
    - •turbulence
    - •crevice volume

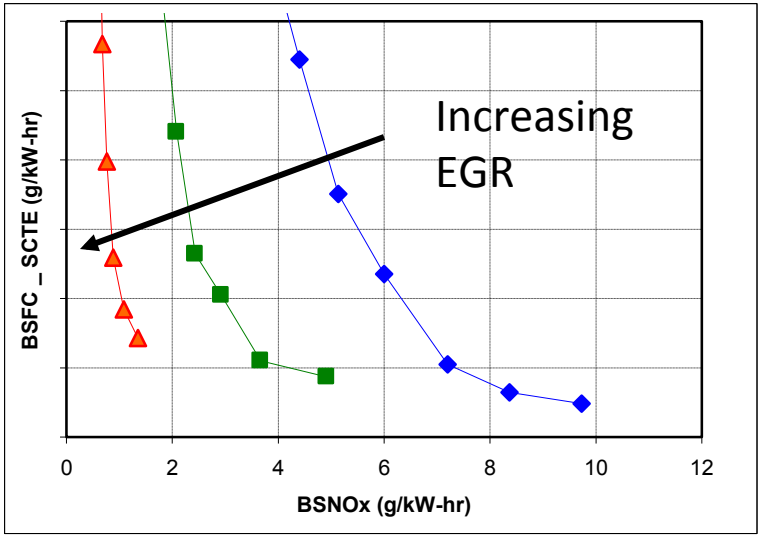
- Injection Pressure
- Bowl Optimization
- Injector Optimization
- Air System Optimization
- Rate Shaping



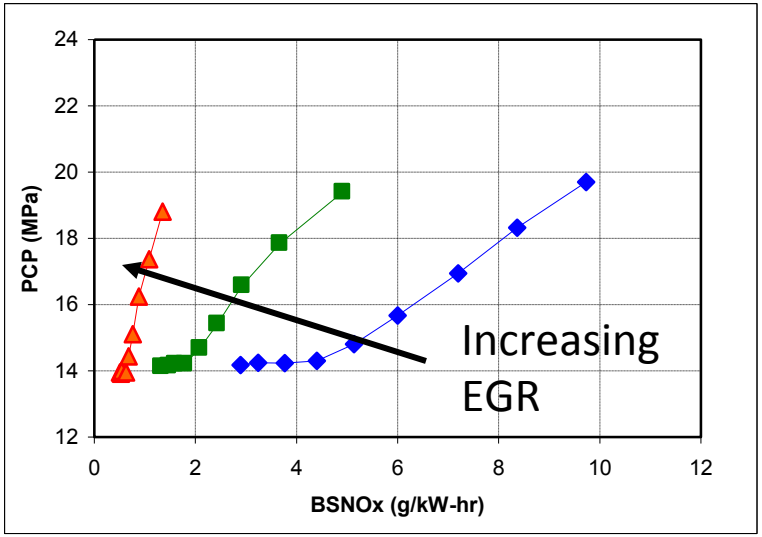
- EGR reduces O2 concentration and also reduces temperature (time for soot oxidation)

Single-Cylinder Test Data

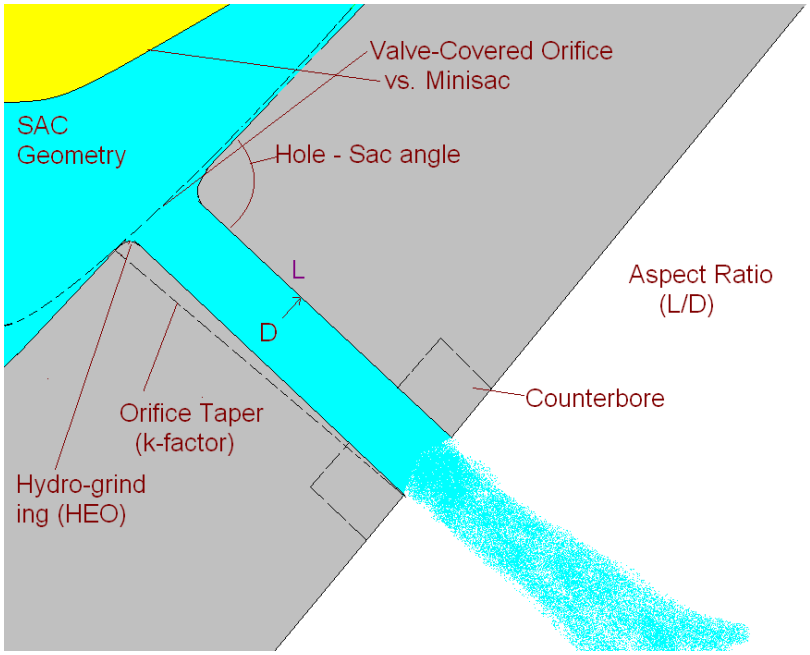


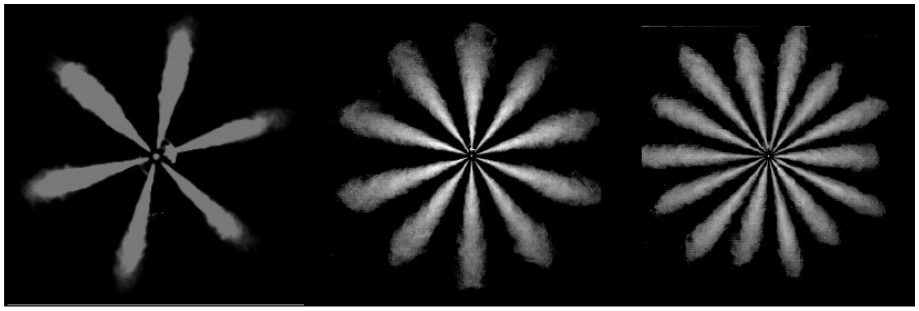


- EGR can significantly improve BSFC at given NOx level
- …does not come for free…soot is a challenge, which requires advanced combustion system
- …and may require an increase in the Peak Cylinder Pressure capability of the engine



Injector Nozzle Configuration

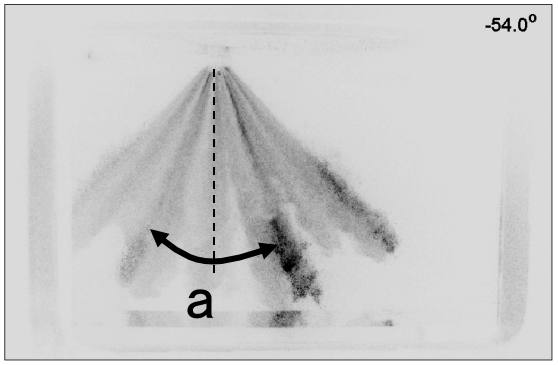




6 hole 10 hole 14 hole

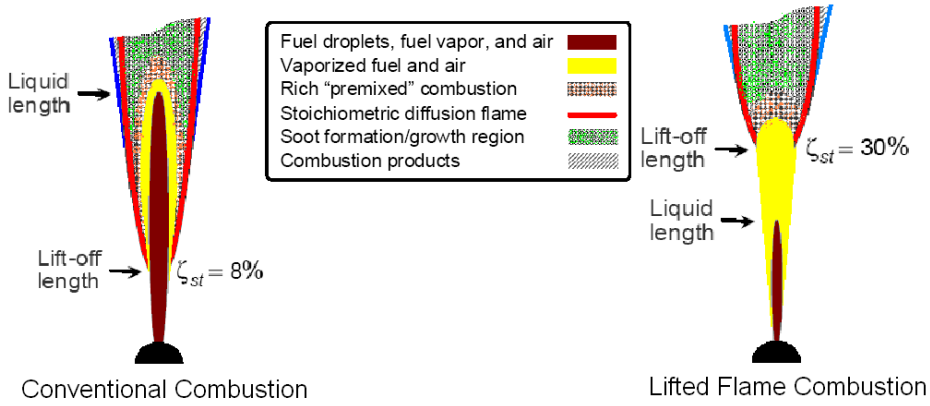
- Included Spray angle
- Spray Targeting
- Number of holes
- Steady Flow (Orifice diam.)
- K-factor
- L/D
- Inlet rounding

1200 rpm, Matching CAT's 300 kPa BMEP, SOI_a ~ -56.5°



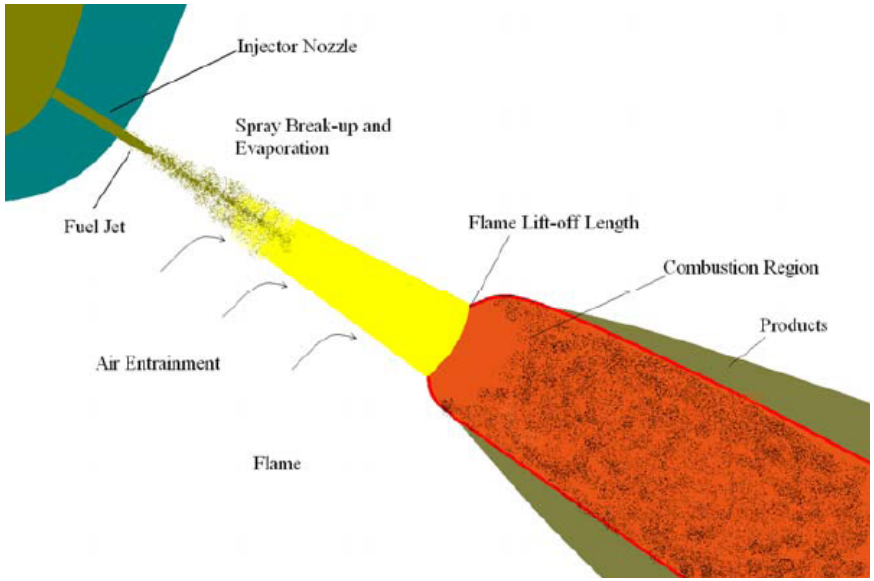
Sootless "Lifted Flame" Concept

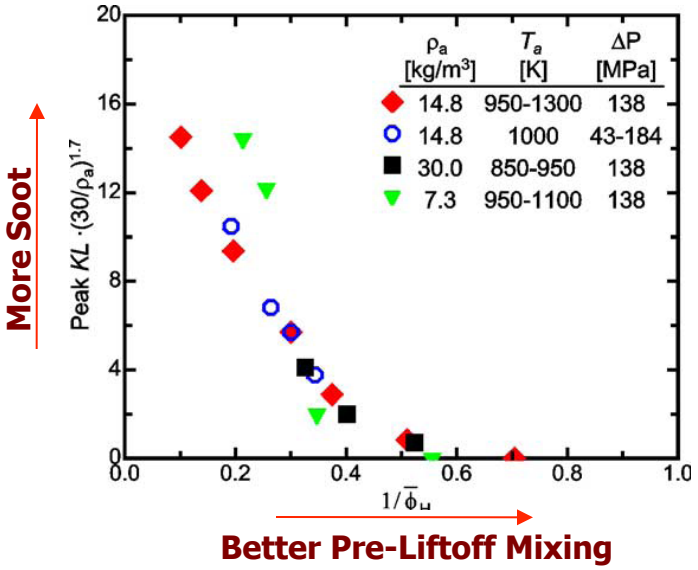
- General idea: pre-mix fuel jet enough prior to lift-off length to enable sootless combustion
- Based on research performed at Sandia Nat'l Labs (Siebers, Pickett, et al.)



Conventional Combustion

Lifted Flame Combustion





Siebers, D., Higgins, B.: SAE Technical Paper 2001-01-0530

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  - Single-Cylinder Optical Research Engine
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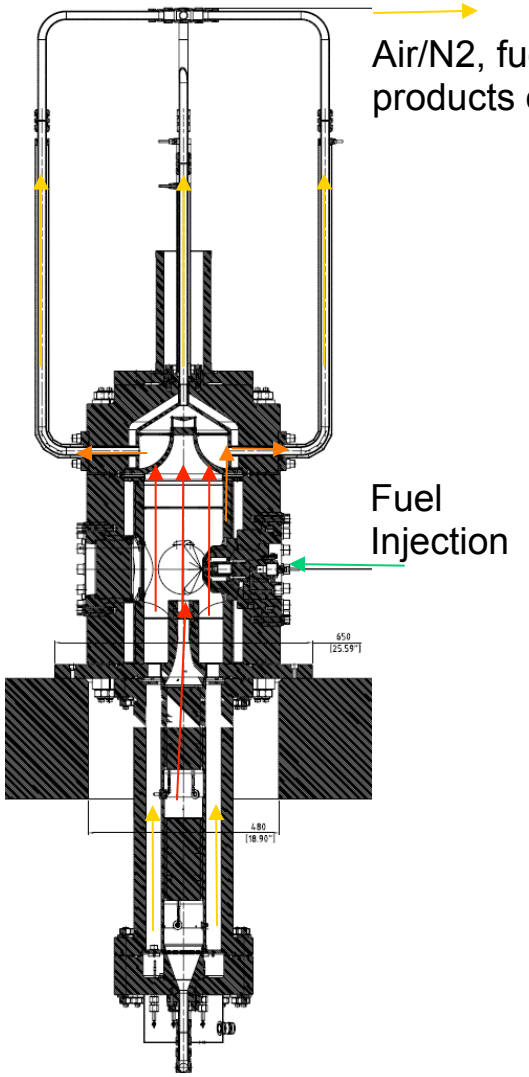
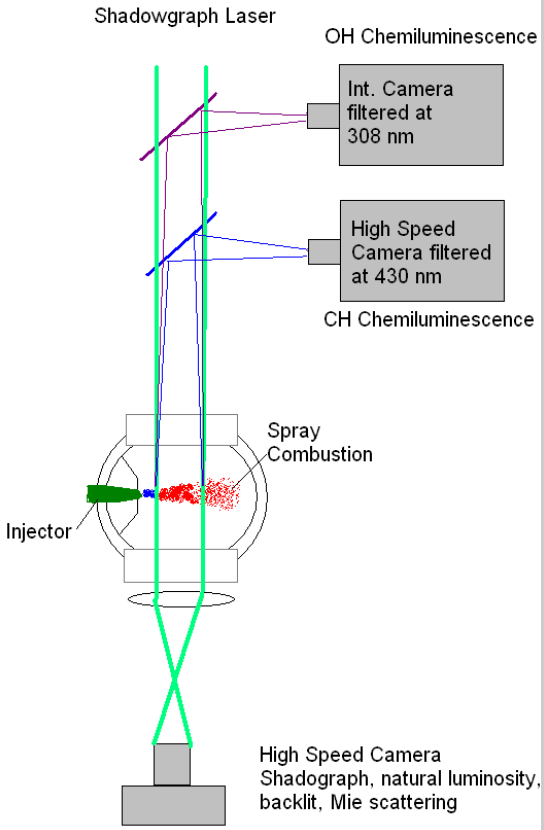
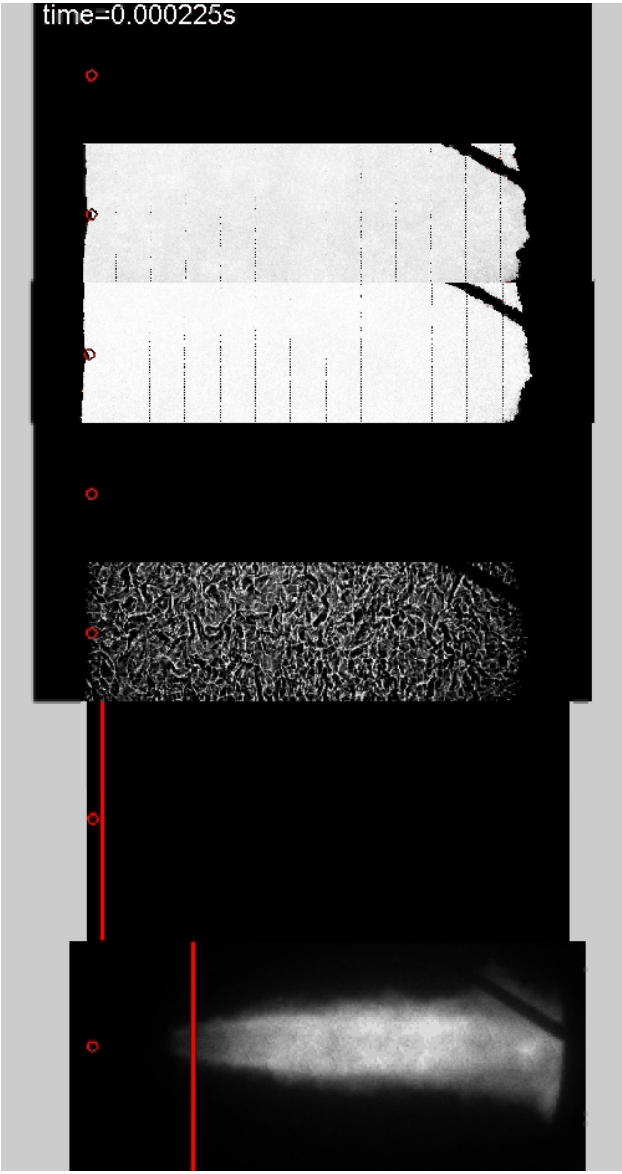
High Temperature Pressure Vessel (HTPV)

Air/N2 in



- World class injection test facility
- Capable of producing in-cylinder TDC-like conditions (1000 K, 15 MPa, 0-20% O_2 with balance N_2)
- Enables quantitative spatial measurements of
  - Heated sprays
  - Combustion experiments
- <u>Use:</u>
  - Evaluate combustion and fuel injector technologies
  - Validate CFD models with quantitative spatial information
  - Diagnose issues with engine combustion system hardware





MIE light scattering off of liquid drops – Non-Combusting (liquid spray behavior, liq. length)

Light blockage – Non-Combusting (liquid spray behavior, liq. length)

Light blockage –Combusting (liquid spray behavior, flame shape)

Broadband natural luminosity (soot location and amount)

Shadowgraph (spray vapor) + flame luminosity (soot visualization)

Light emission filtered at 430 nm CH* chemiluminescence

Transient flame zone visualization

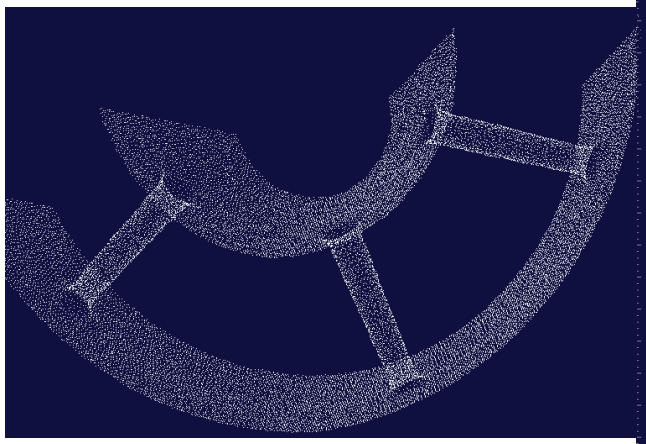
Time-averaged light emission filtered at 308 nm

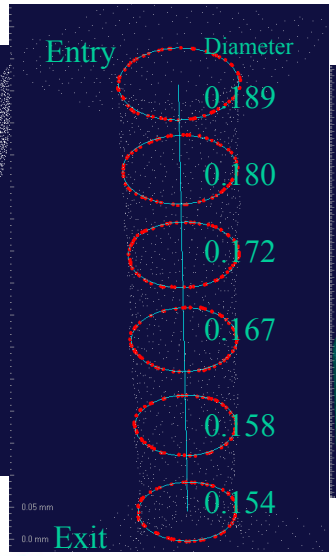
OH* chemiluminescence

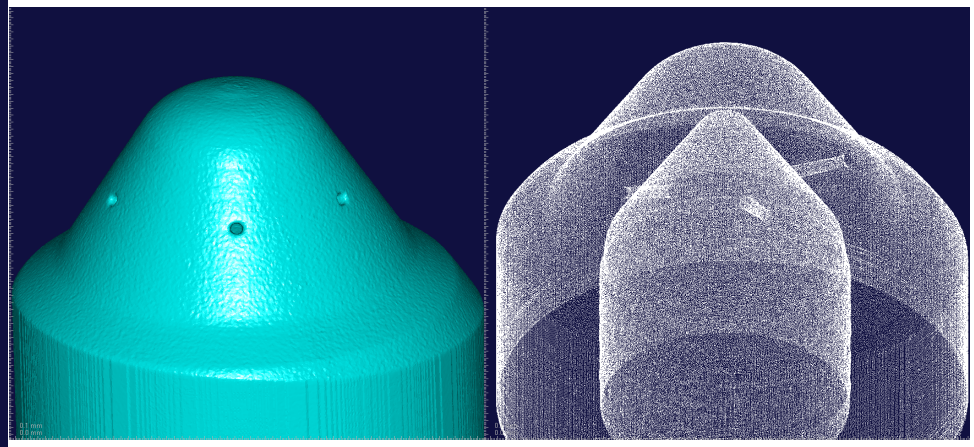
Lift-off length measurement

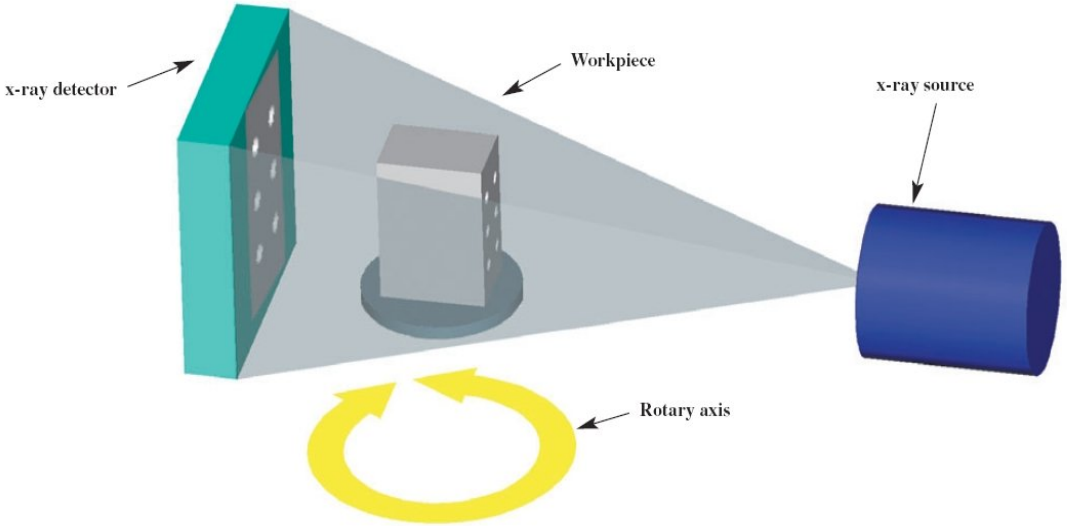
C9 Bowl Size

Nozzle Characterization – X-Ray CT

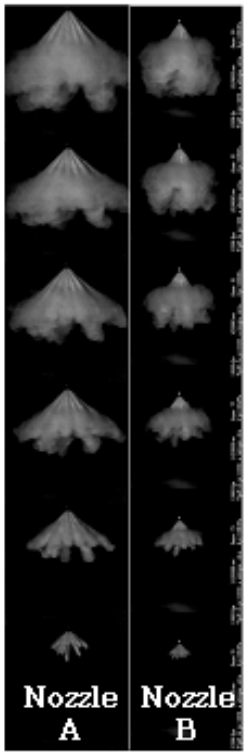


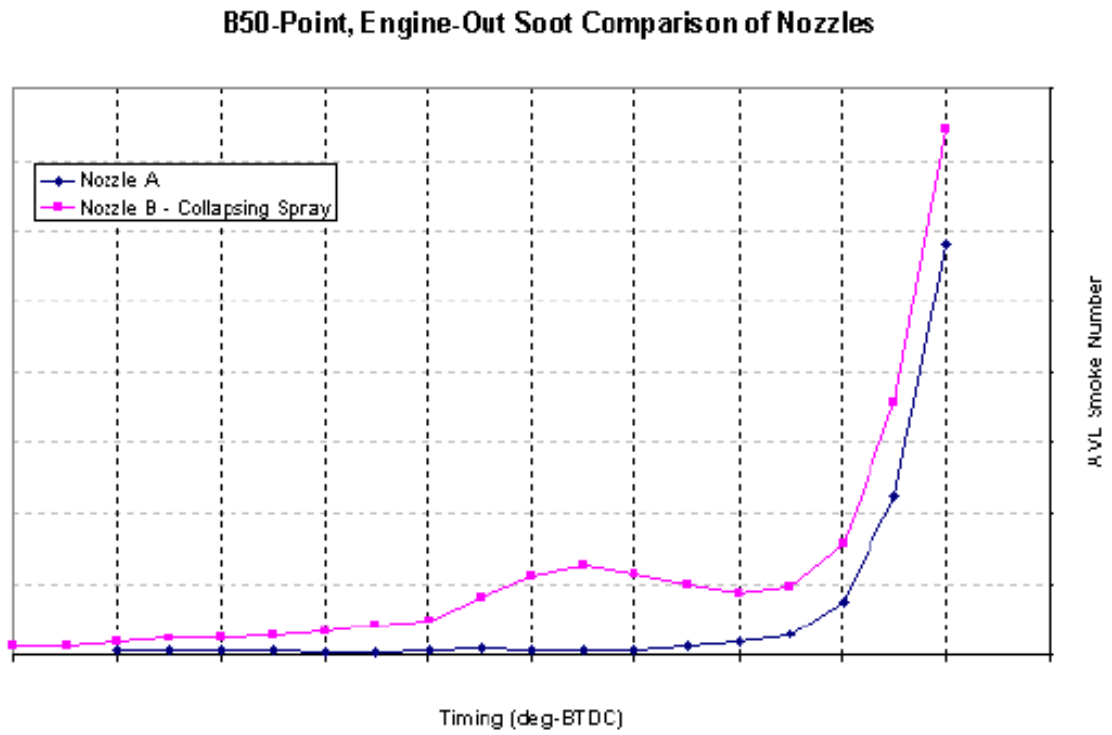






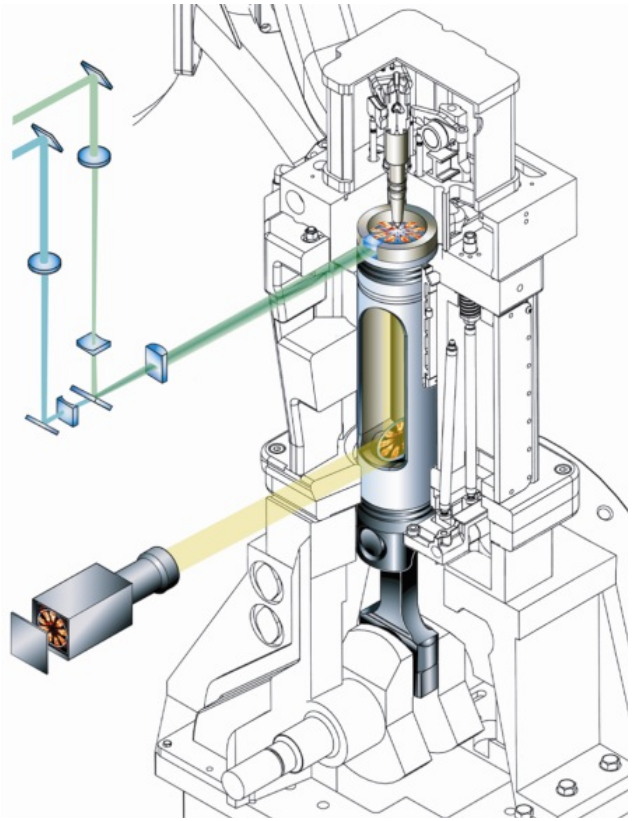
Impact of Nozzle machining



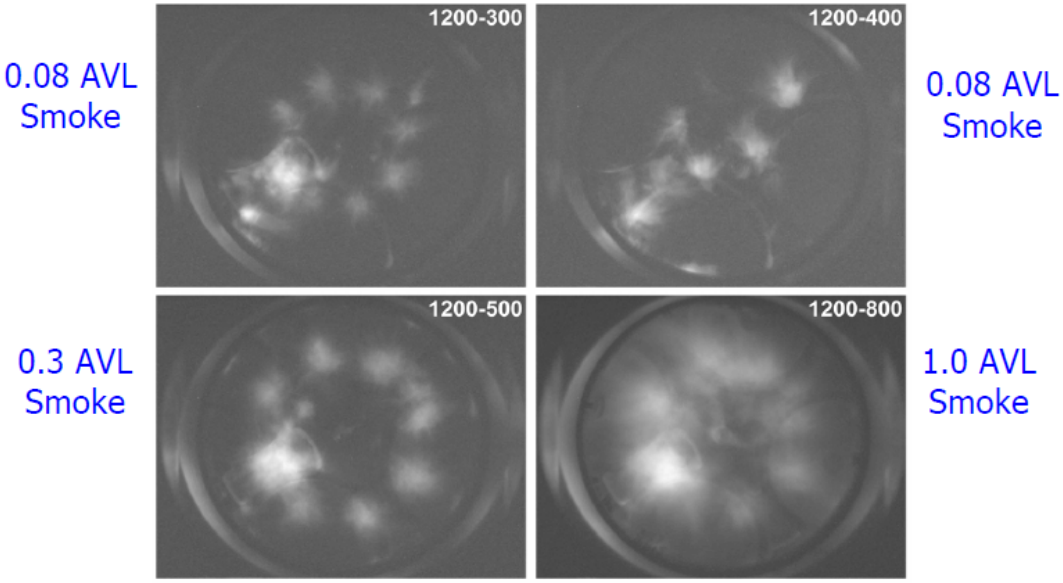


- Nozzles machined to be identical may behave very differently
- Accurate manufacturing is critical

3176 Optical Engine at Sandia National Labs.



- **Sandia 3171 Optical Engine**
- Full optical access
- World-class combustion and spray diagnostics
- Explore advanced nozzle concepts under transient conditions



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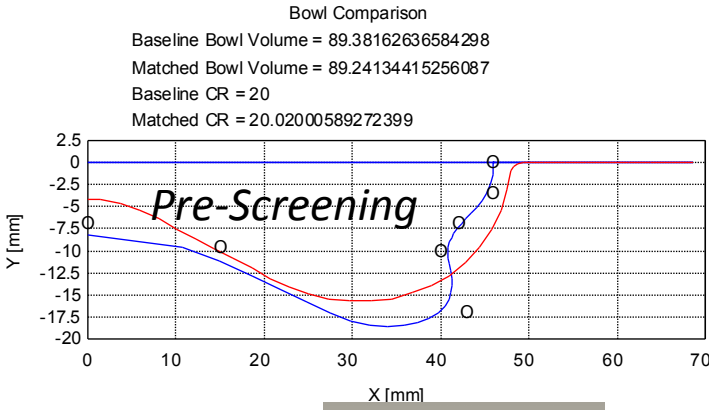
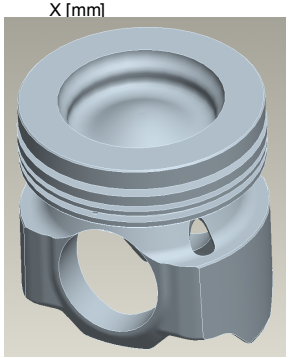
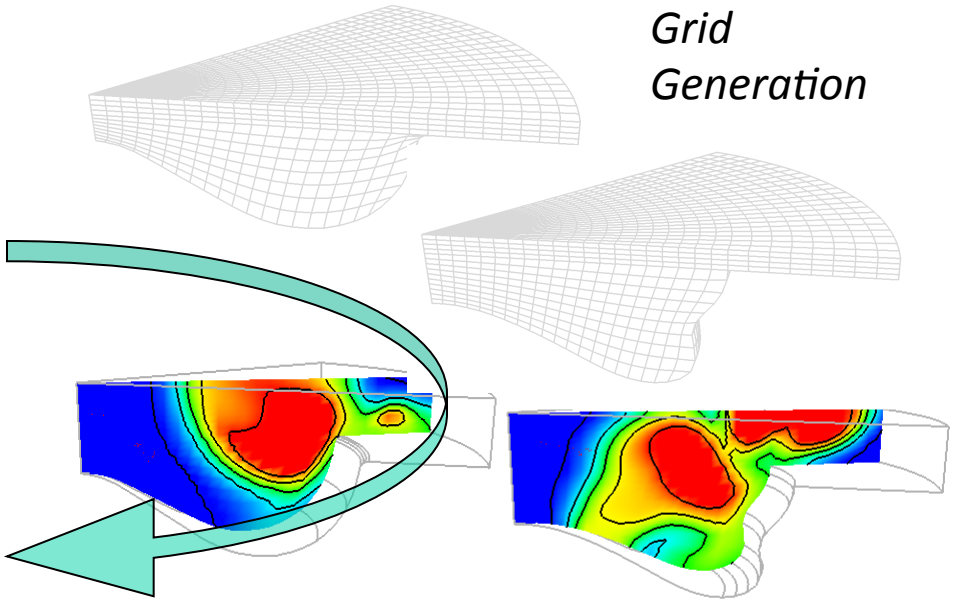
Piston bowl design (+ injector nozzle)

- Provide interaction with spray to promote fuel-air mixing
- Provide good late-cycle mixing to enable soot oxidation
- Minimize deposits and oil contamination



Design, Procurement, Testing

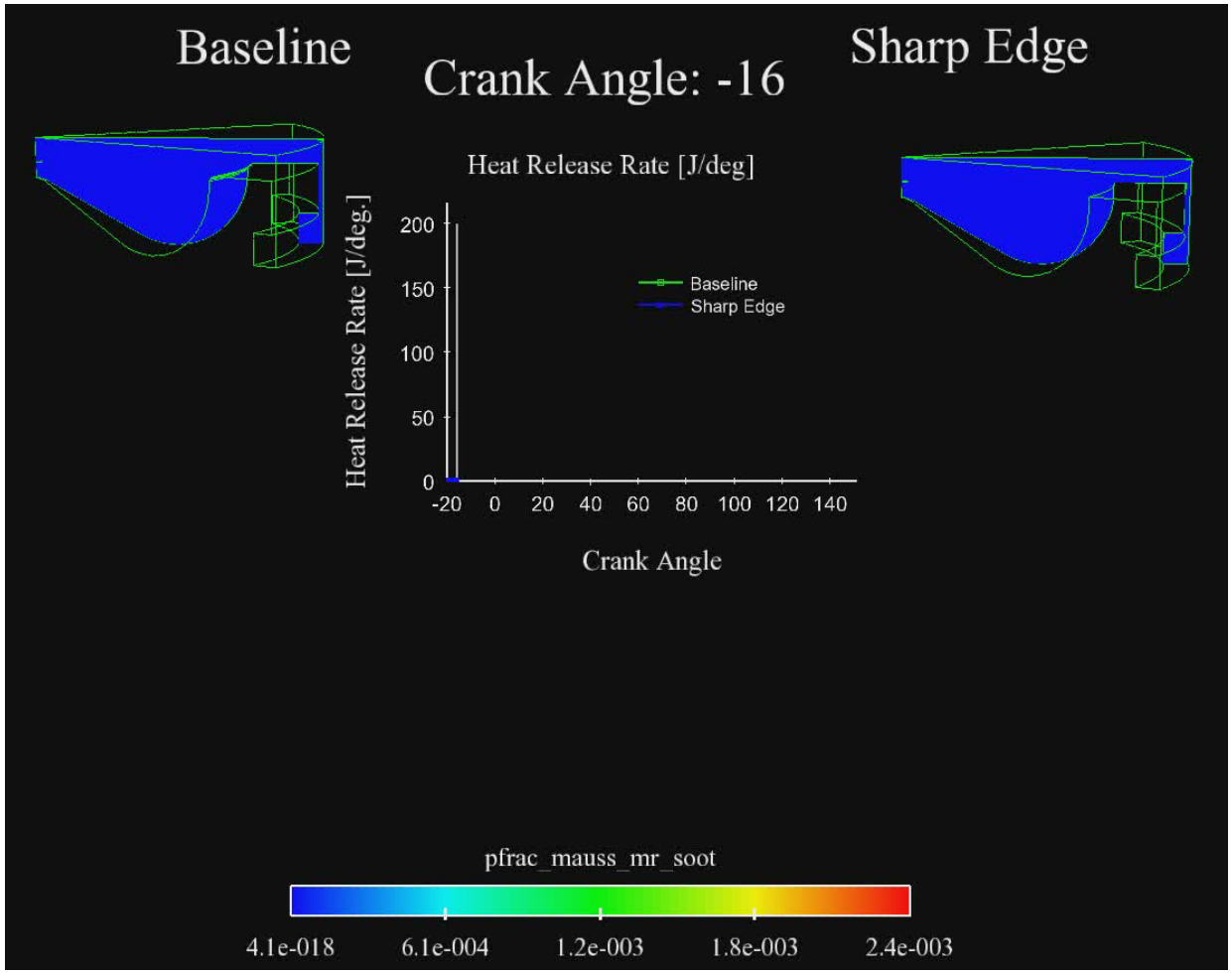




Grid Generation

CFD-Analysis of Promising Designs

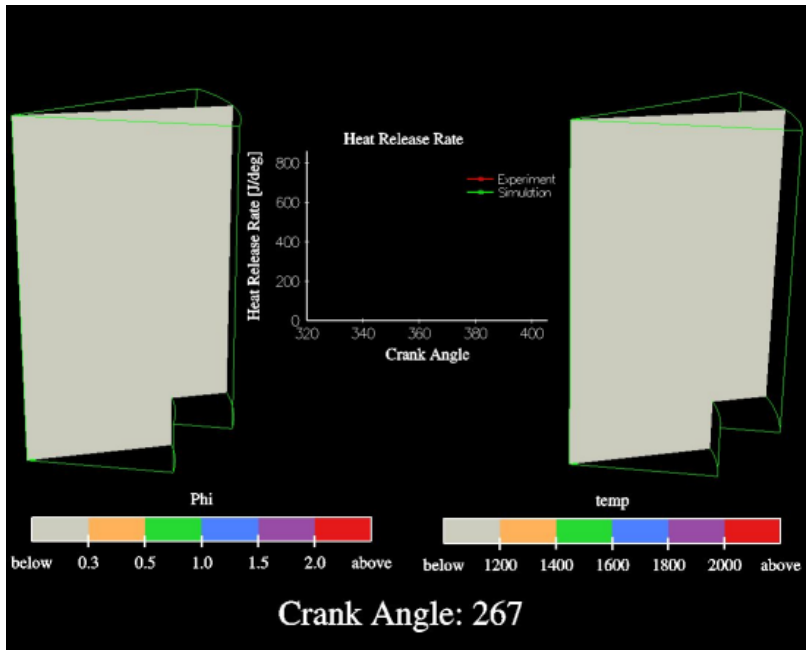
Piston Bowl Shape Comparison

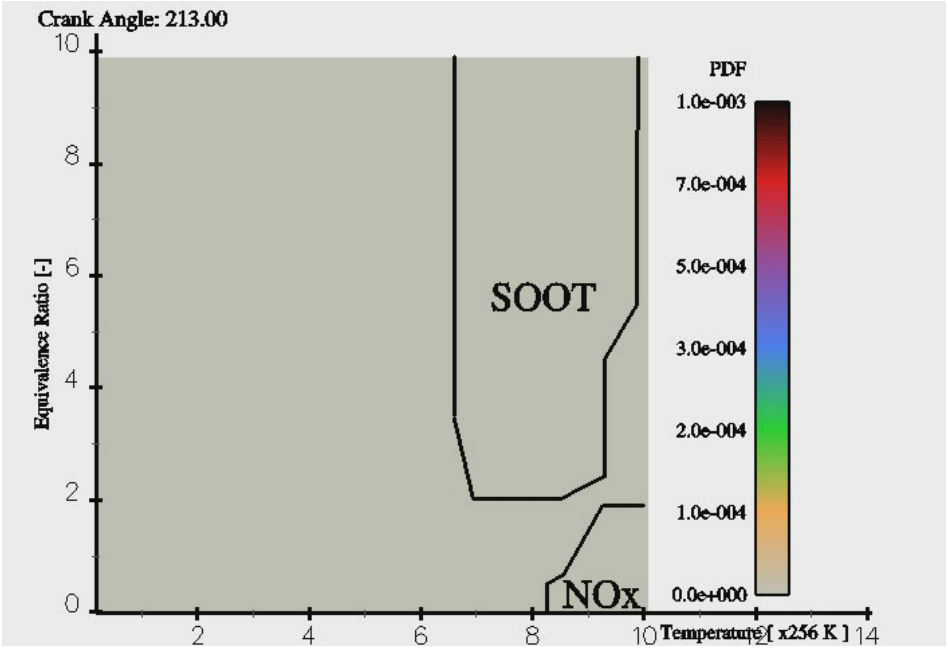


- Improved Soot Oxidation w/ sharp-edged piston bowl
- Less mixture in squish region w/ sharp-edged design
- Heat release rates start deviate at the point where the mixture reaches the bowl rim

Drive Simulation Excellence

Combustion Viz. in Physical as well as Phase Space

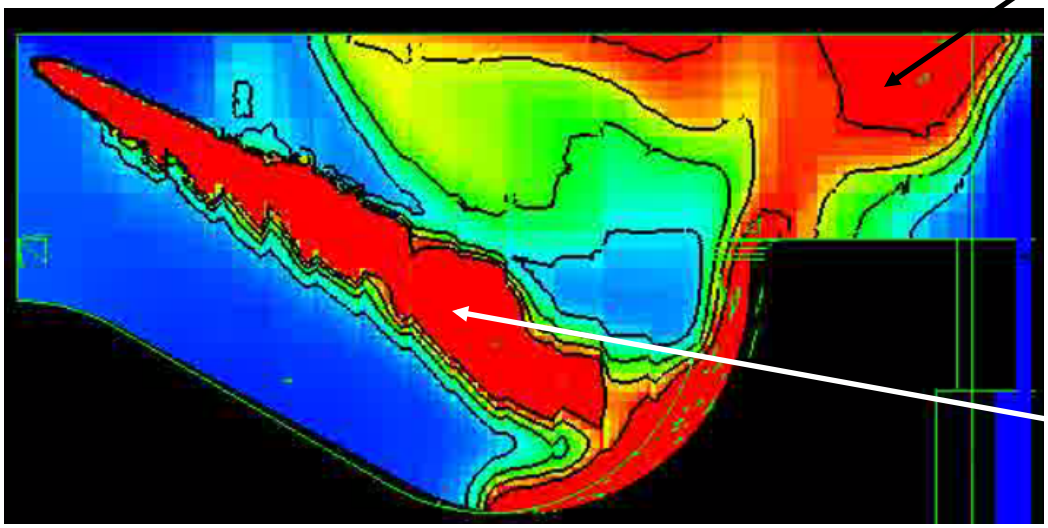




Visualization the combustion process in phase space offers additional insight into mixture stratification and temperature distribution throughout the cycle

Bowl Design Impact on Deposits / Oil Consumption

Combustion CFD



Soot Behavior

• More soot reaching the sensitive areas may lead to:

  • More formation

  • Less oxidation

  • Soot location further from tip

Liquid Fuel

• Impinging and partially oxidizing on piston top or cylinder walls, especially at end of injection or early pilots

• Fuel properties or reaction with oil and partial oxidation

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Some current gaps in our understanding

- Validated chemical mechanisms under dilute and high pressure conditions
- Ability to simulate transient soot emissions efficiently (with respect to time)
- Performance and durability impact of wide range of next generation fuels (diesel and natural gas) on engines and aftertreatment systems

Questions?